

	ID	Title	Description	Current Capabilities	Needed Capabilities
Contrast	CG-2	Coronagraph Optics and Architecture	Coronagraph optics and architecture that suppress diffracted starlight by a factor of $\leq 10^{-9}$ at visible and infrared wavelengths.	<p>6×10^{-10} raw contrast at 10% bandwidth across angles of 3-16 λ/D demonstrated with a linear mask and an unobscured pupil in a static vac lab env't (Hybrid Lyot)</p> <p>$< 8.8 \times 10^{-9}$ raw contrast at 10% bandwidth across angles of 3-9 λ/D demonstrated with a circularly-symmetric mask and obscured pupil in a static vacuum lab env't (WFIRST)</p>	Coronagraph masks and optics capable of creating circularly symmetric dark regions in the focal plane enabling raw contrasts $\leq 10^{-9}$, IWA $\leq 3 \lambda/D$, throughput $\geq 10\%$, and bandwidth $\geq 10\%$ on obscured/segmented pupils in a simulated dynamic vacuum lab environment .
Angular Resolution (plus sensitivity, integration time, and planet yield)	CG-1	Large Aperture Primary Mirrors	Large monolith and multi-segmented mirrors that meet tight surface figure error and thermal control requirements at visible wavelengths.	<p>Monolith: 3.5m sintered SiC with $< 3 \mu\text{m}$ SFE (Herschel) 2.4m ULE with $\sim 10 \text{ nm}$ SFE (HST) Depth: Waterjet cutting is TRL 9 to 14", but TRL 3 to >18". Fused core is TRL 3; slumped fused core is TRL 1.</p> <p>Segmented: 6.5m Be with 25 nm SFE (JWST)</p> <p>Non-NASA: 6 dof, 1-m class SiC and ULE, $< 20 \text{ nm}$ SFE, and $< 5 \text{ nm}$ wavefront stability over 4 hr with thermal control</p>	<p>Aperture: 4m - 12m; SFE $< 10 \text{ nm rms}$ (wavelength coverage 400 nm - 2500 nm)</p> <p>Wavefront stability better than 10 pm rms per wavefront control time step.</p> <p>Segmented apertures leverage 6 DOF or higher control authority meter-class segments for wavefront control.</p> <p>Environmentally tested.</p>
Detection Sensitivity	CG-8	Ultra-Low Noise, Large Format Visible Detectors	Low-noise visible detectors for faint exoplanet characterization with an Integral Field Spectrograph	<p>1kx1k silicon EMCCD detectors provide dark current of $8 \times 10^{-4} \text{ e-/px/sec}$; effective read noise $< 0.2 \text{ e- rms}$ (in EM mode) after irradiation when cooled to 165.15K (WFIRST).</p> <p>4kx4k EMCCD fabricated but still under development.</p>	<p>Effective read noise $< 0.1 \text{ e- rms}$; CIC $< 3 \times 10^{-3} \text{ e-/px/ram}$; dark current $< 10^{-4} \text{ e-/px/sec}$ tolerant to a space radiation environment over mission lifetime.</p> <p>$\geq 2\text{k} \times 2\text{k}$ format</p>
Detection Sensitivity	CG-9	Ultra-Low Noise, Large Format Near Infrared Detectors	Near infrared wavelength (900 nm to 2.5 μm), extremely low noise detectors for exo-earth spectral characterization with Integral Field Spectrographs.	<p>HgCdTe photodiode arrays have read noise $< \sim 2 \text{ e- rms}$ with multiple non-destructive reads; dark current $< 0.001 \text{ e-/s/px}$; very radiation tolerant (JWST).</p> <p>HgCdTe APDs have dark current $\sim 10\text{-}20 \text{ e-/s/px}$, RN $< 1 \text{ e- rms}$, and $< 1\text{k} \times 1\text{k}$ format</p> <p>Cryogenic (superconducting) detectors have essentially no read noise nor dark current; radiation tolerance is unknown.</p>	<p>Read noise $< 1 \text{ e- rms}$, dark current $< 0.001 \text{ e-/px/s}$, in a <u>space radiation environment</u> over mission lifetime.</p> <p>$\geq 2\text{k} \times 2\text{k}$ format</p>
Contrast Stability	CG-6	Segment Phasing Sensing and Control	Multi-segment large aperture mirrors require phasing and rigid-body sensing and control of the segments to achieve tight static and dynamic wavefront errors.	<p>6 nm rms rigid body positioning error and 49 nm rms stability (JWST error budget)</p> <p>SIM and non-NASA: nm accuracy and stability using laser metrology</p>	Systems-level considerations to be evaluated but expect will require less than 10 pm rms accuracy and stability.

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Contrast Stability	CG-7	Telescope Vibration Control	Isolation and damping of spacecraft and payload vibrational disturbances	<p>80 dB attenuation at frequencies > 40 Hz (JWST passive isolation)</p> <p>Disturbance Free Payload demonstrated at TRL 5 with 70 dB attenuation at "high frequencies" with 6-DOF low-order active pointing.</p>	<p>Monolith: 120 dB end-to-end attenuation at frequencies > 20 Hz.</p> <p>Segmented: 140 dB end-to-end attenuation at frequencies > 40 Hz.</p> <p>End-to-end implies isolation between disturbance source and the telescope.</p>
Contrast	CG-3	Deformable Mirrors	Environment-tested, flight-qualified large format deformable mirrors	<p>Electrostrictive 64x64 DMs have been demonstrated to meet $\leq 10^{-9}$ contrasts and $< 10^{-10}$ stability in a vacuum environment and 10% bandwidth; 48x48 DM passed random vibe testing.</p>	<p>4 m primary: $\geq 96 \times 96$ actuators 10 m primary: $\geq 128 \times 128$ actuators</p> <p>Enable raw contrasts of $\leq 10^{-9}$ at ~20% bandwidth and IWA $\leq 3 \lambda/D$</p> <p>Flight-qualified device and drive electronics (radiation hardened, environmentally tested, life-cycled including connectors and cables)</p> <p>Large segment DM needs possible for segmented telescopes.</p>
Contrast Stability	CG-5	Low-Order Wavefront Sensing and Control	Sensing and control of line of sight jitter and low-order wavefront drift	<p>< 0.5 mas rms per axis LOS residual error demonstrated in lab with a fast-steering mirror attenuating a 14 mas LOS jitter and reaction wheel inputs; ~ 100 pm rms sensitivity of focus (WFIRST).</p> <p>Higher low-order modes sensed to 10-100 nm WFE rms on ground-based telescopes.</p>	<p>Sufficient fast line of sight jitter (< 0.5 mas rms residual) and slow thermally-induced (≤ 10 pm rms sensitivity) WFE sensing and control to maintain closed-loop $< 10^{-9}$ raw contrast with an obscured/segmented pupil and simulated dynamic environment.</p>
Contrast	CG-4	Post-Data Processing	Post-data processing techniques to uncover faint exoplanet signals from residual speckle noise at the focal-plane detector.	<p>Few 100x speckle suppression has been achieved by HST and by ground-based AO telescopes in the NIR and in contrast regimes of 10^{-4} to 10^{-5}, dominated by phase errors.</p>	<p>A 10-fold contrast improvement in the visible from 10^{-9} raw contrast where amplitude errors are expected to be important (or a demonstration of the fundamental limits of post-processing)</p>